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STRESS CONCENTRATION AROUND INCLINED HOLES IN PRESSURIZED THICK-WALLED CYLINDERS

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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Photoelastic investigation has been conducted to study stress concentration around inclined holes in pressurized thick-walled cylinders. It has been found that an inclination in the transverse plane reduces the stress concentration and an inclination in the meridianal plane increases the stress concentration. Also, the stress concentration depends upon the bore-to-hole diameter ratio among other parameters.

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Charles Cobb's participation in the experimental phase of this investigation is hereby acknowledged.

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NOMENCLATURE

R,θ,Z	Cylindrical coordinate system, Z coincides with the axis of the cylinder.
r,ϕ,z	Cylindrical coordinate system, z coincides with the axis of the hole.
R_1,R_2	Inside and outside radius of the cylinder, respectively.
r_1	Radius of the hole.
$\sigma_r,\sigma_\phi,\sigma_\theta$	Normal stress along the r,ϕ,θ direction, respectively.
p	Pressure.
K	Stress concentration factor.
c	Ellipticity, i.e., the ratio of the major/minor axis of an ellipse.
α	Angle of inclination in the $R\theta$-plane.
β	Angle of inclination in the RZ-plane.
$X,Y;x,y$	Rectangular coordinate systems.
N	Fringe intensity; i.e., fringe per unit thickness.
f	Material fringe value.

INTRODUCTION

The service life or load carrying capacity of pressurized cylinders with holes is dependent upon stress concentrations at the holes. As a result, a knowledge of the stresses at the bore-hole interface is important because many thick-walled cylinders contain holes for lubrication, valves, and other purposes. In high pressure applications, the state of stress in a cylinder with holes is needed because fatigue life is very critical and present day weight limitation prevents high factors of safety. The purpose of our investigation concerns itself with the stress concentration at evacuator holes in gun tubes. Evacuator holes are small holes inclined to the tube axis. This investigation includes holes in the transverse (RΘ) plane as well as those in the meridianal (RZ) plane. The effects of bore-to-hole-diameter ratio and the angle of inclination on stress concentration were determined. The results are given and future work is suggested

LITERATURE SURVEY

A survey of the literature shows that in 1956, Fessler and Lewin[1] determined the stress distribution in a tee-junction of thick pipes subjected to internal pressure. Analytically, they treated cylindrical laminae of the main pipe as infinite flat plates, each with a circular hole, under the action of two perpendicular tensions and an internal

[1] H. Fessler and B. H. Lewin, "Stress Distribution in a Tee-Junction of Thick Pipes," British Journal of Applied Physics, Vol. 7, pp. 76-79, February 1956.

pressure p acting in the hole. The perpendicular tensions are the theoretical hoop (Lame) and axial stresses which would act on the particular laminae of the main pipe if the branch did not exist. They obtained approximate solutions for stresses σ_ϕ and σ_r when the ratio r_1/R_1 is small, as follows:

$$\sigma_\phi = \frac{R_2{}^2 R_1{}^2 p}{2(R_2{}^2 - R_1{}^2)} \left[\left(\frac{1}{R^2} + \frac{2}{R_2{}^2}\right) + \frac{r_1{}^2}{r^2}\left(\frac{1}{R^2} + \frac{2}{R_1{}^2}\right) + \frac{\cos 2\phi}{R^2}\left(1 + \frac{3r_1{}^4}{r^4}\right)\right] \quad (1)$$

$$\sigma_r = \frac{R_2{}^2 R_1{}^2 p}{2(R_2{}^2 - R_1{}^2)} \left[\left(\frac{1}{R^2} + \frac{2}{R_2{}^2}\right) - \frac{r_1{}^2}{r^2}\left(\frac{1}{R^2} + \frac{2}{R_1{}^2}\right) - \frac{\cos 2\phi}{R^2}\left(1 - \frac{4r_1{}^2}{r^2} + \frac{3r_1{}^4}{r^4}\right)\right] \quad (2)$$

The stress σ_ϕ has a maximum value at the junction where $R = R_1$, $r = r_1$ and $\phi = 0$. Thus

$$\sigma_{\phi max} = \frac{4R_2{}^2 + R_1{}^2}{R_2{}^2 - R_1{}^2}\, p \quad (3)$$

and the stress concentration factor (ratio of $\sigma_{\phi\ max}$ to the Lame hoop stress without the hole)

$$K = \sigma_{\phi max}/\left[\left(\frac{R_2{}^2 + R_1{}^2}{R_2{}^2 - R_1{}^2}\right)p\right] = \frac{4R_2{}^2 + R_1{}^2}{R_2{}^2 + R_1{}^2} \quad (4)$$

They also performed a three-dimensional photoelastic experiment using a model with $R_2 = 3R_1$ and $R_1 = 2r_1$. A value of $\sigma_{\phi,max} = 3.50$ p and $K = 2.80$ were obtained experimentally in comparison with the calculated value of $\sigma_{\phi,max} = 4.62$ p and $K = 3.70$. The calculated K is 32% greater than the experimental value, probably indicating that $R_1 = 2r_1$ is too large for equation (1) to be applicable.

In 1965, Little[2], Little and Bagci[3] showed that stress concentration has a higher value

$$K = \frac{4R_2{}^2+2R_1{}^2}{R_2{}^2+R_1{}^2} \tag{5}$$

in open-end cylinders under internal pressure. They also showed stress concentrations for small inclined holes in the transverse (RΘ) plane as well as those in the meridianal (RZ) plane. In the former case, the holes are not radial except for those having a zero angle of inclination. The contour of the hole on the bore of the cylinder, when the angle of inclination is small, was approximately represented by an ellipse with major axis perpendicular to the Z-direction. Stress concentration occurs at the ends of both major and minor axes. At the ends of the major axis, they have a value of

$$K = \frac{2(c-1)R_2{}^2+R_1{}^2}{R_2{}^2+R_1{}^2} \tag{6}$$

for closed-end cylinders, and

$$K = \frac{2(c-1)R_2{}^2-2cR_1{}^2}{R_2+R_1{}^2} \tag{7}$$

for open-end cylinders. At the ends of minor axis, they have a value of

$$K = \frac{(4R_2{}^2/c)+R_1{}^2}{R_2{}^2+R_1{}^2} \tag{8}$$

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[2] R. E. Little, "Stress Concentrations for Holes in Cylinders," Machine Design, Dec. 23, 1965, pp. 133-135.

[3] R. E. Little and C. Bagci, "Stress Analyses of Pressurized Cylinders," Engineering Research Bulletin, Publication No. 145, Oklahoma State University, March 1965.

for closed-end cylinders, and

$$K = \frac{(4R_2^2/c)+2R_1^2}{R_2^2+R_1^2} \quad (9)$$

for open-end cylinders. In the latter case, the hole becomes an ellipse with its major axis parallel to the Z-direction. Stress concentration occurs at the ends of the major axis. They have a value of

$$K = \frac{4cR_2^2+R_1^2}{R_2^2+R_1^2} \quad (10)$$

for closed-end cylinders, and

$$K = \frac{4cR_2^2+2R_1^2}{R_2^2+R_1^2} \quad (11)$$

for open-end cylinders. No experimental work has been shown. They pointed out that inclinations in the RZ plane should be avoided since K would be very large from equations (10) and (11) with a high value of c.

In 1968, O'Hara[4] reported a photoelastic investigation on stress concentration factors on holes inclined in the transverse ($R\theta$) plane. In a closed-end cylinder of $R_2 = 1.75R_1$, O'Hara reported an experimental value of K of 2.75, 2.95 and 2.46 for radial holes (zero inclination) of $R_1 = 20r_1$, $10r_1$, and $5r_1$, respectively, in comparison with a calculated value of 3.26 from Eq. (4). The calculated stress concentration factor is 14% greater than the average experimental value

[4]G. P. O'Hara, "Experimental Investigation of Stress Concentration Factors of Holes in Thick Walled Cylinders," Watervliet Arsenal Technical Report WVT-6807, June 1968.

(neglecting the result from $R_1 = 5r_1$). His data on inclined holes were not informative since his photoelastic observation was made along the axis of the hole (z-direction) and σ_ϕ was not determined.

In 1972, Gerdeen[5,6] published analytical and experimental results, and concluded that the optimum configuration of a thick-walled cylinder with a radial hole in the transverse plane is one with equal bore and hole diameters.

In summary, published results show that calculated stress concentration factors at radial holes are higher than those obtained experimentally. No experimental work on inclined holes is available.

EXPERIMENTS AND RESULTS

Models. Three cylinders having an inside diameter of 3 1/8 in. and outside diameter of 5 3/4 in. were machined from epoxy resin rods supplied by PHOTOLASTIC under trade name PLM4B. They were closed on both ends with caps containing holes for pressure inlet and manometer connections. Twenty-four holes with three radii, four angles of inclination α, in the RΘ-plane, and four angles of inclination, β, in the RZ-plane were distributed among these cylinders, as shown in Table 1. The angular and axial separations between holes were sufficient such that no interaction of stresses between holes were observed. These holes were sealed at the outside wall of the cylinder. These cylinders

[5] J. C. Gerdeen, "Analysis of Stress Concentrations in Thick Cylinders With Sideholes and Crossholes," Journal of Engineering for Industry, Vol. 94, No. 3, pp. 815-824, Aug 1972.

[6] J. C. Gerdeen and R. E. Smith, "Experimental Determination of Stress-Concentration Factors in Thick-Walled Cylinders with Crossholes and Sideholes," EXPERIMENTAL MECHANICS, Vol. 12, No. 11, pp. 530-536, Nov 1972.

were stress-frozen at an internal pressure of 10 psi with a calibration disk. The Lame hoop stress at the inside wall of the cylinder, without hole, had a value of $(R_2^2+R_1^2)p/(R_2^2-R_1^2)$ = 18.4 psi and the material had a fringe value of 1.95 psi.

TABLE 1. HOLE GEOMETRIES, R_2/R_1 = 1.84

Hole	R_1/r_1	α	β	α_1	α_2
1	20	0	0	- 2.9°	2.9°
2	10	0	0	- 5.7°	5.7°
3	5	0	0	-11.5°	11.5°
4	20	18.5°	0	15.5°	21.5°
5	10	17.5°	0	11.5°	23.6°
6	5	15.5°	0	3.8°	27.8°
7	20	39.3°	0	35.7°	43.1°
8	10	36.9°	0	30.0°	44.4°
9	5	32.2°	0	19.5°	47.1°
10	20	71.8°	0	64.2°	90°
11	10	64.2°	0	53.1°	90°
12	5	53.1°	0	3[illegible].9°	90°
13	20	0	0		
14	10	0	0		
15	5	0	0		
16	20	0	20°		
17	10	0	20°		
18	5	0	20°		
19	20	0	40°		
20	10	0	40°		
21	5	0	40°		
22	20	0	60°		
23	10	0	60°		
24	5	0	60°		

NOTE: α_1 and α_2 are defined in Figure 1.

Slicing. Stress concentration factor K was computed as the ratio of the maximum value of σ_ϕ to the Lame hoop stress without the hole. It is known that σ_ϕ attains its maximum at the inside wall of the cylinder. Hence, wall thickness of the cylinders was reduced to 0.10 in by removing materials from the outside wall and leaving materials at the inside wall untouched. After thickness reduction, these cylinders were cut into twelve sections, each containing two holes with an angular separation of about 180 degrees.

Shape of Hole on the Inside Wall as Seen Along the R-Direction

A. Holes in the RΘ-Plane, $\beta = 0$. Let the bore of the cylinder be represented by

$$X^2 + Y^2 = R_1{}^2 \tag{12}$$

and the hole by

$$x^2 + y^2 = r_1{}^2 \tag{13}$$

The direction of observation, R-direction, is defined by α, the angle of inclination, Figure 1, and is normal to the tangential plane T containing the point of tangency D having its coordinates $R_1\sin\alpha$ and $R_1\cos\alpha$. The projection of the contour PDQDP of the hole on a plane S parallel with the tangential plane T gives the shape of the hole as seen radially. Let A, defined simultaneously by coordinates (X,Y) and (x,y) be a point on the contour and $A'(x',y')$ be the projection of A on the S-plane. From geometric consideration, Figure 1, we have

$$\overline{QA}^2 = [(R_1\sin\alpha+r_1)-X]^2 + \{Y-[R_1{}^2-(R_1\sin\alpha+r_1)^2]^{1/2}\}^2 \tag{14}$$

and

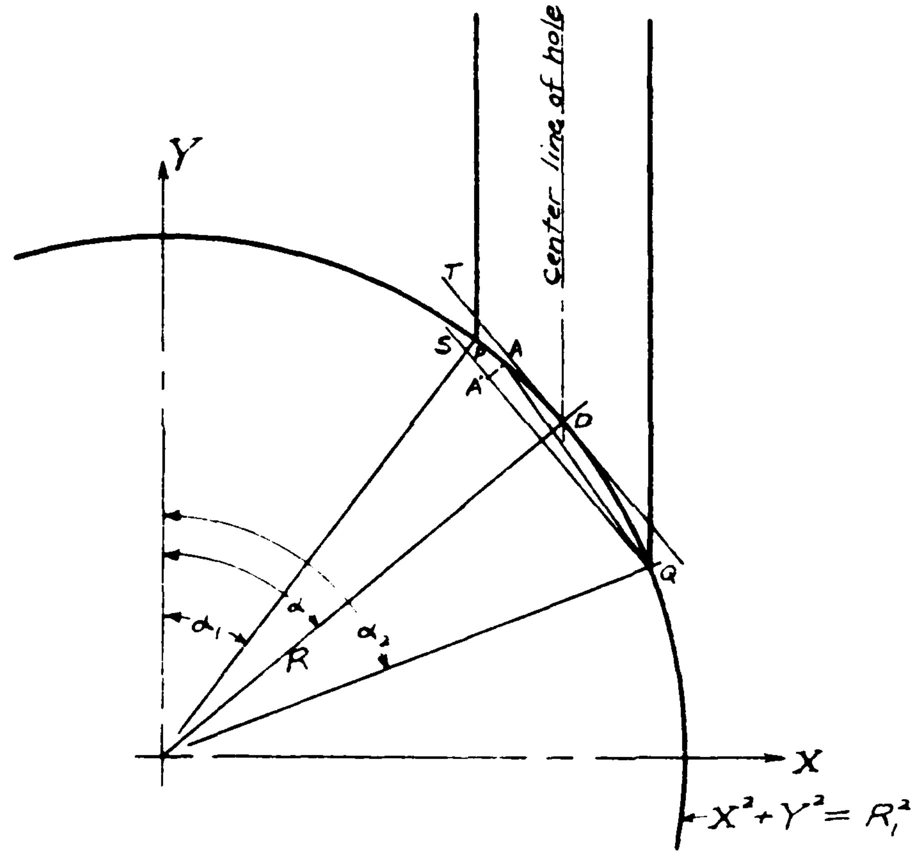

Figure 1. Projection of holes, $\alpha \neq 0$, $\beta = 0$

$$AQA' = 90°-\alpha-\tan^{-1}\frac{R_1\sin\alpha+r_1-X}{Y-[R_1{}^2-(R_1\sin\alpha+r_1)^2]^{1/2}} \tag{15}$$

It follows that

$$x' = \overline{QA}\cos AQA'$$

$$= \overline{QA}\sin[\alpha+\tan^{-1}\frac{R_1\sin\alpha+r_1-X}{Y-[R_1{}^2-(R_1\sin\alpha+r_1)^2]^{1/2}} \tag{16}$$

and

$$y' = y \tag{17}$$

Figure 2 shows the projections of holes 4 through 12. It can be seen that they can not be represented by ellipses.

B. Holes in the RZ-Plane, $\alpha = 0$. In this case, the projection is an ellipse and can be expressed as

$$(x')^2 + (y'\cos\beta)^2 = r_1{}^2 \tag{18}$$

where y' is parallel with the Z-direction.

Photoelastic Observation. A transmission polariscope having a monochromatic (5461Å) collimated light source was used in this investigation. An immersion tank and immersion fluid having the same refractive index as the model material were employed to eliminate refraction and reflection of light rays at the surface of the slice. The polarizer and quarter-wave plate were situated at the center of the cylindrical slice so that only one half of the cylinder was within the field of polarized light. In this way, photoelastic observation of the individual hole could be made without interference of the other. Adjustments for rotating the cylinder inside the tank were provided such that observation could be always made along the R-direction.

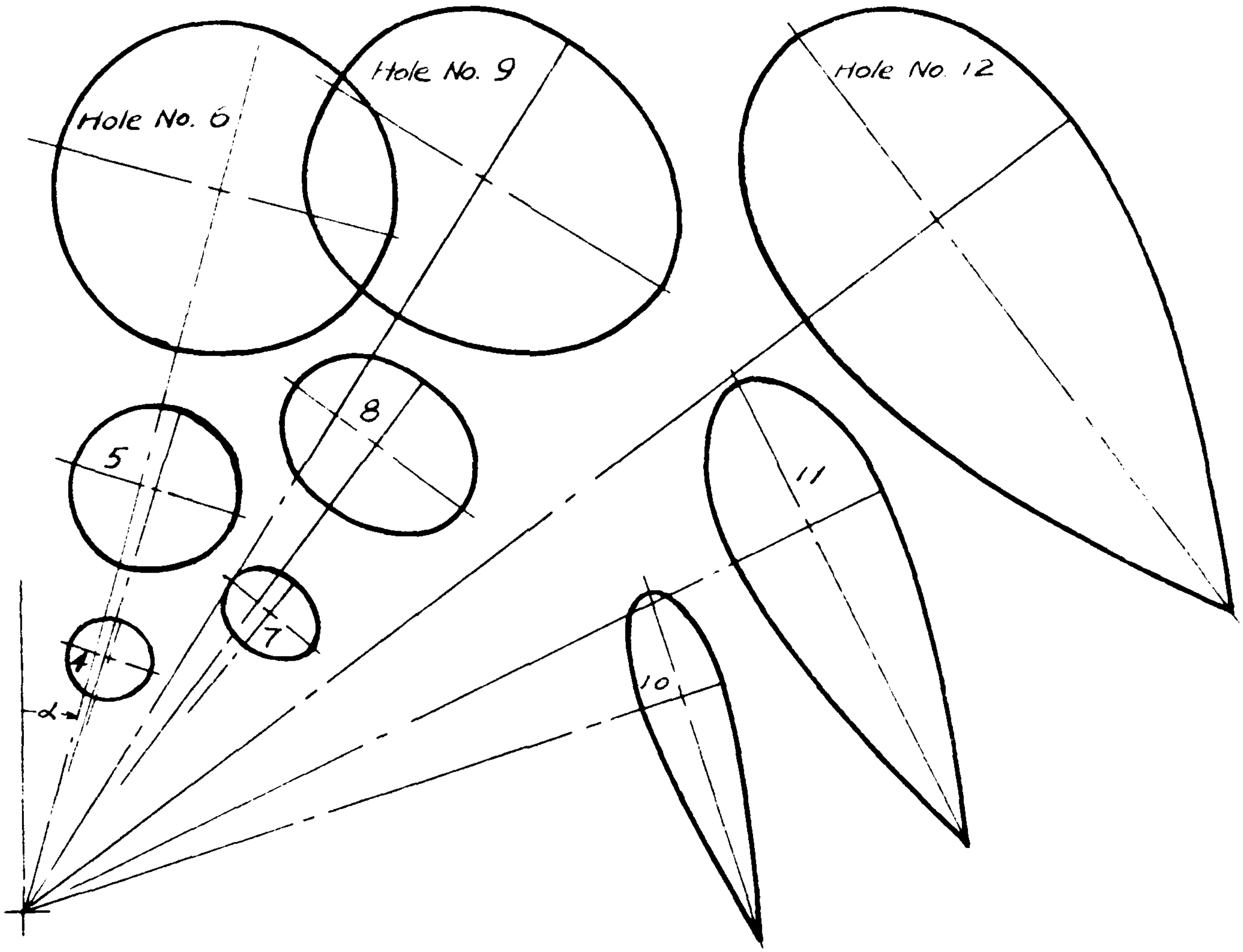

Figure 2. Shape of holes on the inside wall as seen along the R direction

One observation at $\alpha = 0$ was made for holes 1 to 3 and 13 to 24. For holes 4 to 12, three observations were made, one each at α, α_1, and α_2, Figure 1 and Table 1. Photographs of isochromatic fringes were taken from each observation, and fringe intensity, N, was calculated.

Experimental Results. From the linear relationship between fringe order and the principal stress difference, we have, at the hole

$$Nf = \sigma_\theta - p \tag{19}$$

and

$$\sigma_\theta = Nf + p \tag{20}$$

For holes 1 to 3 and 13 to 15, maximum value of N was found at point M, Figure 3, where σ_θ is equivalent to σ_ϕ. For holes 4 to 12, maximum value of N was also found at M, not at L nor R. Thus

$$\sigma_{\phi,max} = N_{max} f + p \tag{21}$$

and

$$K = \sigma_{\phi,max}/18.4 \tag{22}$$

The stress concentration factors, photoelastically determined as well as calculated from Eqs. (4), (8), and (10), are shown in Table 2. Data from holes 10, 11, 12, 16, 17, 19 and 22 were lost due to material breakage during slice preparation. Figure 4 shows curves of K versus α and β at constant values of R_1/r_1. These results show that (a) for $\alpha = \beta = 0$, K decreases as R_1/r_1 decreases; (b) for $\beta = 0$ and a constant R_1/r_1, K decreases as α increases, and (c) for $\alpha = 0$, K increases as β increases. It also shows that calculated values are too high. Moreover, it can be seen that an inclination in the RΘ-plane reduces the stress concentration. However, an inclination in the RZ-plane raises the stress concentration.

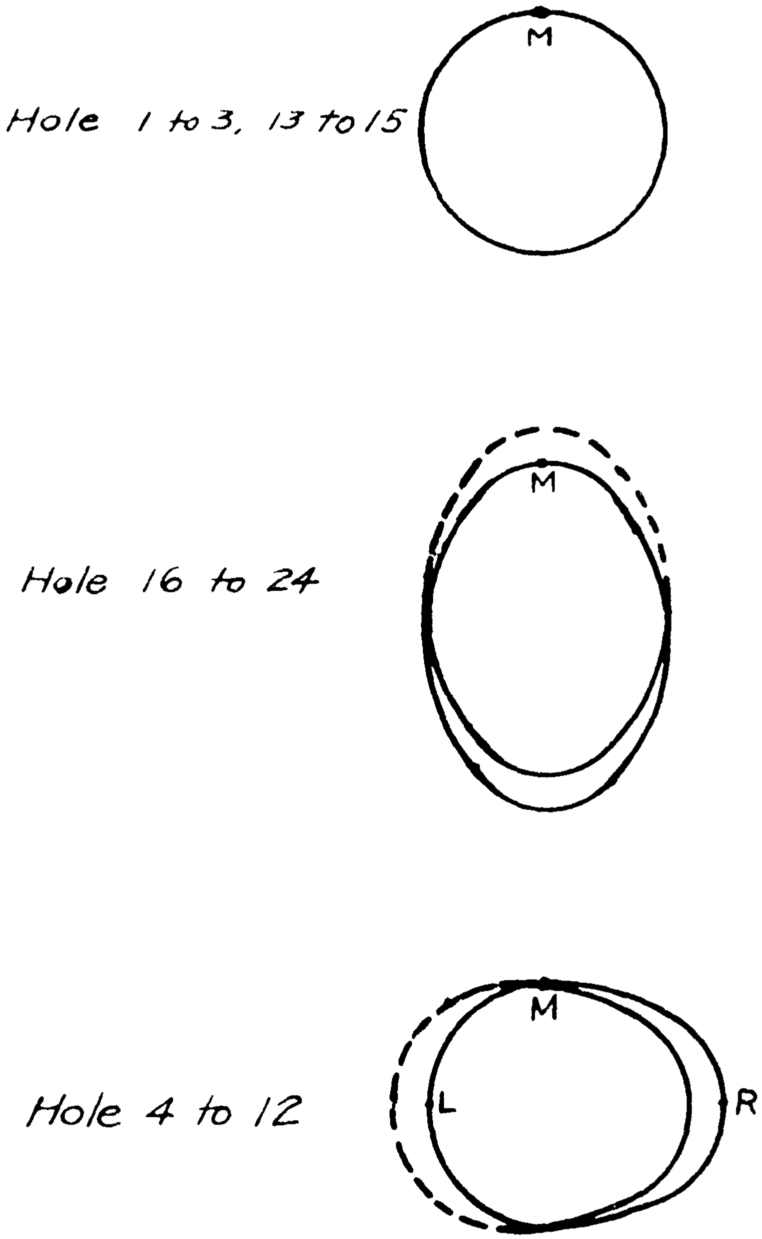

Figure 3. Position of maximum fringe intensity

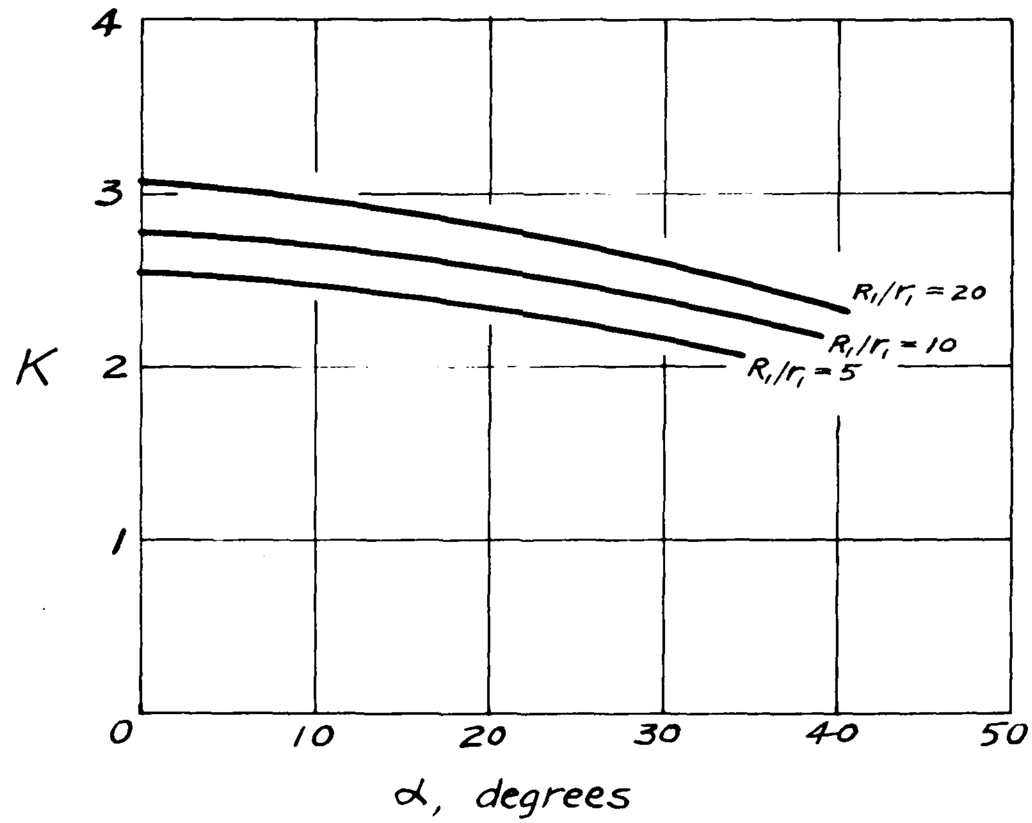

Fig. 4(a). K versus α at constant values of R_1/r_1, $\beta = 0$.

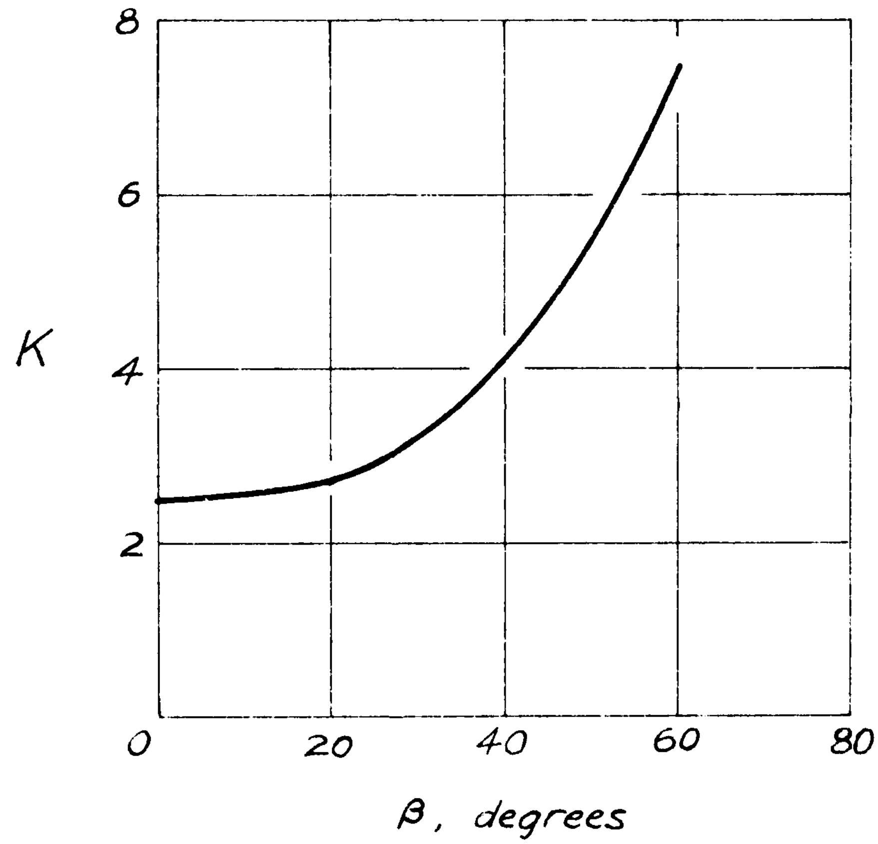

Fig. 4(b). K versus β; $\alpha = 0$, $R_1/r_1 = 5$

TABLE 2. STRESS CONCENTRATION FACTORS, $R_2/R_1 = 1.84$

Hole	R_1/r_1	α	β	K Photoelasticity	K Calculated	
1	20	0	0	2.99	3.32	Eq. 4
2	10	0	0	2.69	3.32	
3	5	0	0	2.64	3.32	
4	20	18.5°	0	2.81	3.16	Eq. 8
5	10	17.5°	0	2.58	3.17	
6	5	15.5°	0	2.50	3.20	
7	20	39.3°	0	2.35	2.61	
8	10	36.9°	0	2.23	2.68	
9	5	32.2°	0	2.08	2.81	
10	20	71.8°	0			
11	10	64.2°	0			
12	5	53.1°	0			
13	20	0	0	3.15	3.32	Eq. 4
14	10	0	0	2.88	3.32	
15	5	0	0	2.36	3.32	
16	20	0	20°			
17	10	0	20°			
18	5	0	20°	2.69	3.51	Eq. 10
19	20	0	40°			
20	10	0	40°	2.84	4.26	
21	5	0	40°	4.21	4.26	
22	20	0	60°			
23	10	0	60°	6.33	6.40	
24	5	0	60°	7.35	6.40	

CONCLUSIONS

1. It has been shown that the shape of the hole inclined in the RΘ-plane, as seen radially, does not appear as an ellipse. Hence, Equation (8) is not applicable.

2. Although the shape of the hole inclined in the RZ-plane, as seen radially, appears as an ellipse, equation (10) considers only an elliptical through-the-wall hole instead of an inclined hole.

3. From the results of holes 1 to 3 and 13 to 15, it shows that equation 4 is limited to a high value of R_1/r_1.

4. All three analytical equations (4, 8, 10) have not taken the size of the hole into account. Experimental results show that stress concentration factors depend on the bore-to-hole ratio, i.e., the size of the hole, and other parameters.

5. Stress concentration factors are reduced by inclining in the RΘ-plane and are raised by inclining in the RZ-plane. Hence, an inclination in the RZ-plane should be avoided.

SUGGESTIONS

Evacuator holes in gun tubes are small holes inclined to the tube axis. It has been found from present investigations that this type of inclination increases the stress concentration. It might be beneficial to investigate the effect of superposing an inclination in the RΘ-plane with that in the RZ-plane. It is hoped that the reduction of K from an inclination in the RΘ-plane will partially compensate the increasing of K from an inclination in the RZ-plane. Also, it might be useful to conduct experiments under open-end conditions.

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